OPTIMIZING CYANIDATION PARAMETERS FOR PROCESSING OF BLENDED FORT KNOX AND TRUE NORTH ORES AT THE FORT KNOX MINE

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Abstract

The Fort Knox Mine is an open-pit operation, located in Alaska, which started commercial production in March 1997. A conventional Mill processes 38,000 tpd of a low grade (1.0 g/t Au) free milling gold ore with a low sulphide component (below 1%). Gold production (11% from gravity and 89% from cyanidation) exceeds 400,000 ounces per year. Short retention time (20h), low temperature (7°C) and low grade make high leaching kinetics critical for the performance of the process. In April 2001, the treatment of True North ore, which represented 14.4% of the mill throughput and contained more sulphide in the form of pyrite, arsenopyrite and stibnite, resulted in a substantial drop in the average gold extraction from 87% to 72.6%. Laboratory investigations indicated that the addition of lead nitrate increased gold extraction to 91.7%. Further investigations were initiated to determine the leaching parameters and the nature of the problem. Subsequently, a lead nitrate addition scheme was implemented at the Fort Knox Mill that resulted in 2002 gold production being in excess of 31,000 ounces higher than that estimated for the non-lead nitrate reagent scheme. This paper presents the results of laboratory investigations and modifications in plant operating practices.

Introduction

The Fort Knox and True North mines are owned by Kinross Gold Corporation and operated by Fairbanks Gold Mining, Inc. (FGMI), a 100% owned subsidiary of Kinross Gold. The Fort Knox mine, located 40 kilometers northeast of Fairbanks, Alaska, is a 91.3 million metric ton resource at a grade of 0.8 g/t Au. The ore is free milling at a relatively coarse grind (65%-100 mesh), has a gravity recoverable gold (GRG) content of 30-65% and has relatively little sulfide mineralization. The True North mine is located 15 kilometers northeast of the Fort Knox processing facility and contains an estimated 6.4 million metric tons at an average grade of 1.5 g/t Au. Gold mineralization is more variable in the True North reserve with a GRG content less than 4% and can be associated with sulfides. Ore from the True North mine is trucked to Fort Knox facility where it is blended with Fort Knox ore and represents approximately 25% of the annual material processed through the mill facility at an average rate of 38,000 tpd.

The ore is blended at the primary gyratory crusher located at the edge of the Fort Knox mine where the material is reduced to -8 inch prior to being conveyed to the coarse ore stockpile at

the mill. Reclaimed ore is processed through a conventional SABC circuit (1) to produce a final product averaging 65% -100 mesh. A simplified process flowsheet is presented in Figure 1.

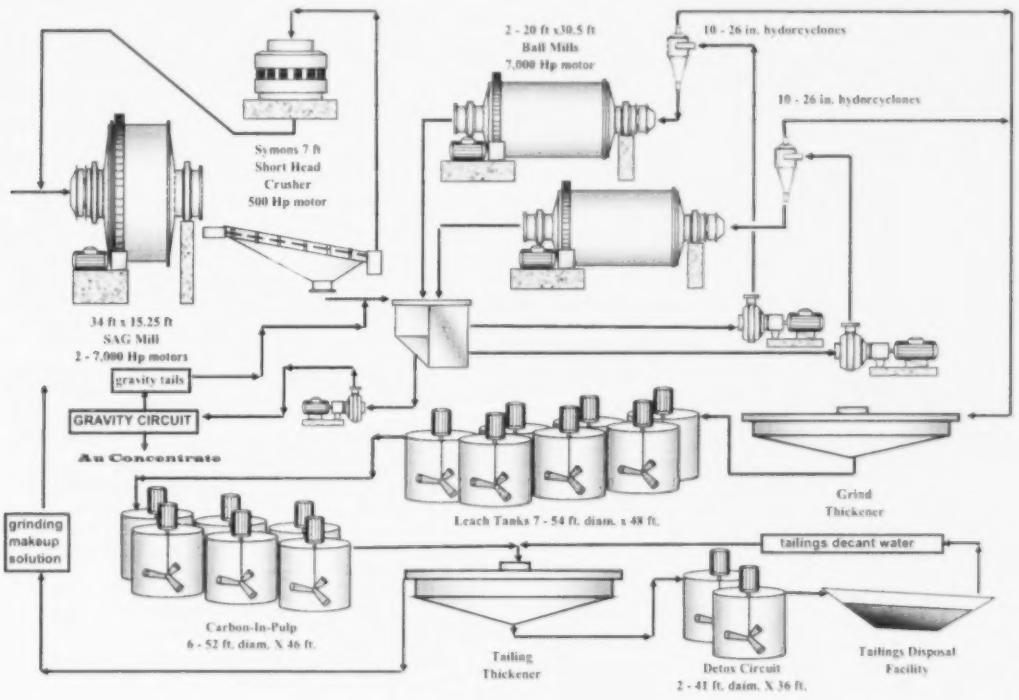

Figure 1: Fort Knox mill process flowsheet.

A split of the grinding circuit circulating load is processed through a gravity plant where approximately 30% of the GRG value of the mill feed is recovered. The remaining gold is extracted and recovered from the ground slurry through a conventional leach/CIP circuit. The CIP tails discharge to a tailings thickener where approximately 60% of the spent leach solution is recycled prior to processing in the cyanide destruction circuit and subsequent placement in the tailings impoundment.

The Fort Knox mill began processing a blend of True North ore in April of 2001. Within two weeks, the plant recovery dropped by approximately 20% and numerous processing approaches were attempted. Ultimately, the True North ore was campaigned through the mill for the majority of second and third quarter of 2001 while a better understanding of the circuit dynamics was developed.

At that time, a detailed evaluation of the cyanidation plant tails was conducted in association with the Mineral Industry Research Center at the University of Alaska Fairbanks. Laboratory results representing this evaluation were previously presented [2] and described the reduction in gold extraction resulting from processing blended True North and Fort Knox ore. Also, presented was evidence that lead nitrate substantially improved the results and had no

significant environmental impact on tailings pond chemistry during operations or at closure. Government agency approvals were received and a lead nitrate addition scheme was implemented in December 2001.

In addition, FGMI entered into an agreement with the Mining and Mineral Sciences Laboratories, CANMET, Natural Resources Canada to perform additional laboratory investigations in the 3rd quarter of 2001. The initial focus of the work was to determine the impact lead nitrate addition would have on gold extraction in the remaining True North reserve that produced poor results under standard cyanidation conditions and typically contain higher sulfide mineralization. This material was ultimately found to be refractory and gold extraction was not significantly improved by any of the cyanidation variables (cyanide concentration, lead nitrate addition, oxygen addition, pH, CIL, particle size and temperature) evaluated [3]. The results were consistent with those produced by the FGMI met lab, where it was also determined that blending of this material with a composite of Fort Knox ore did not have the adverse effects being seen in the plant. A second True North ore composite was sent to CANMET for the remainder of the work.

A composite of blasthole reject material from both the True North and Fort Knox mine is built each month and represents the ore shipped to the Fort Knox mill. The Fort Knox sample and second True North sample, sent to CANMET, were splits of the February 2002 composite from each mine. The FGMI laboratory has developed procedures that allow for successful simulation of the Fort Knox leach circuit performance. The laboratory equipment at the mine does not, however, allow for maintaining the controlled conditions required to test a number of the variables known to impact gold leach kinetics and overall extraction. Therefore, the composites were sent to CANMET for a controlled cyanidation study to develop a better understanding of the leach parameters and more specifically, the nature of the interference on gold extraction when the two ores are blended. Results from the second True North sample blended with the Fort Knox ore sample are presented in this paper. Also, included is a comparison between the CANMET results and FGMI lab results for February as well as the YTD comparison between the FGMI lab and actual Fort Knox leach circuit gold extractions.

CANMET Laboratory Investigation

A blend sample of 20 kg was produced by mixing the Fort Knox ore and the True North ore sample in a ratio of 3:1 in a drum tumbler under nitrogen atmosphere for 6 hours. The sample was then divided into 1000 g lots using a rotary separator. Representative samples were taken for chemical, mineralogical and screen analysis. Table I shows the results of chemical and mineralogical analysis.

The gold content, obtained by fire assay, was 0.71 g/t (duplicate). The mineralogy was determined by quantitative backscattered electron image analysis. As shown in Table I, 99% of the sample consisted of gangue minerals: quartz, albite, chlinochlore, orthoclase, montmorillonite, muscovite, and calcite. Small amount (0.6%) of iron oxides (geothite, hematite, ilmenite and sphene) and trace amounts of sulfides (0.09%) including pyrite, arsenopyrite, pyrrhotite, arseniosiderite, stibnite, chalcopyrite, pentlandite, cervantite and monazite were found in the sample. There were antimony minerals at 0.01%, (stibnite and cervantite) in the sample [4].

The lime, sodium cyanide, lead nitrate, compressed air and oxygen were all certified reagent grade chemicals. All the cyanidation tests were conducted in jacketed glass cells which allowed accurate control of the pulp temperature. The cap of the test cell has four openings which allowed mechanical agitation of the pulp, injection of air/oxygen, monitoring of the pulp pH and dissolved oxygen. Lime, sodium cyanide and a mixture of air and oxygen were added to the pulp to maintain the preset target value. The experimental details used for cyanidation were described in a previous paper by Deschênes and Fulton [5].

Table I - Mineralogical and Chemical Analysis of the Blend Sample
(Fort Knox Sample: True North Sample = 3: 1)

Chemical Analysis		Mineralogical analysis
Element	Content (%)	
Au	0.71 g/t	
Ag	0.22 g/t	Major phases 99.01%
Si	31.06	quartz, albite,
Al	6.64	chlinochlore, orthoclase,
Fe	2.65	montmorillonite,
Ca	1.95	muscovite, and calcite
Mg	0.78	
C_{total}	0.76	Minor phases 0.59%
S	0.03	goethite, rutile and
As	0.069	ilmenite
Zn	0.02	
Sb	0.009	Trace phases
Pb	0.003	arsenopyrite 0.14%
Cu	0.002	pyrite 0.11%
Ni	0.002	pyrrhotite 0.04%
Co	0.002	arseniosiderite 0.01%
Hg	0.0004	stibnite 0.01%
Bi	0.0007	chalcopyrite 0.01%
Te	<0.0008	monazite 0.01%
		pentlandite 0.003%
		cervantite 0.003%
		galena 0.004%

Leachable Gold

In order to test the leachability of the gold in the blend sample, tests were conducted in duplicate at 98% - 400 mesh, pH: 10.2, DO: 12 ppm, 200 ppm NaCN, duration of cyanidation: 48 hours, temperature: 21°C, and with the addition of 100 g/t lead nitrate. The results are shown in Figure 2.

The results indicate that 95.8% of the gold in the blend sample could be leached out within 48 hours (average residue at 0.03 g/t Au), which indicates that the second True North ore sample was easier to leach than the first True North ore sample. Fine grinding accelerated the leaching rate over the initial cyanidation period, and an extraction of 91% could be achieved

within 6 hours, which is the time required to reach a steady state. Additional liberation of gold enhanced the extraction. The cyanide consumption for the leachable gold tests was increased significantly. The additional liberation of sulphide minerals also enhanced the reaction with cyanide. An average of 0.20 kg/t NaCN was consumed in the 48-hour cyanidation, while only 0.04 kg/t NaCN was consumed for the baseline test as shown in Figure 3.

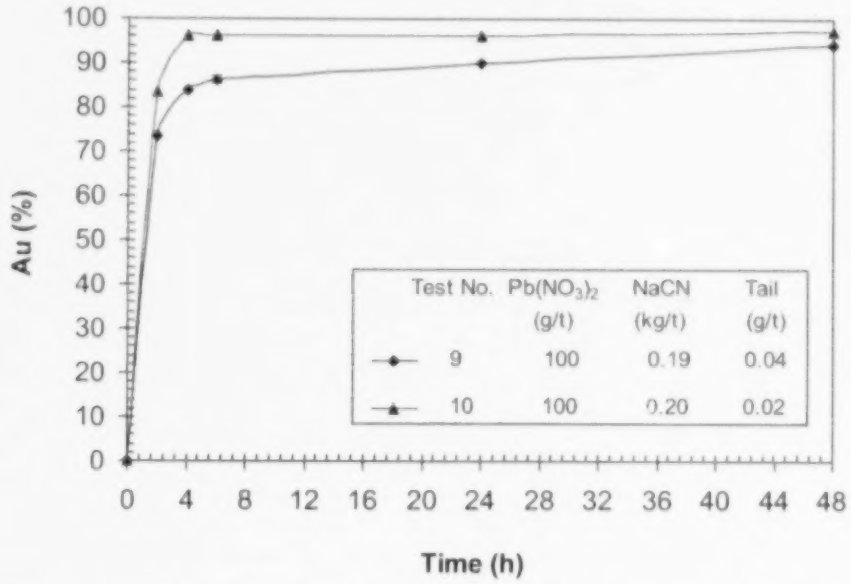

Figure 2: Leachable gold of the blend sample from Fort Knox. pH: 10.2; DO: 12 ppm; 100 g/t $Pb(NO_3)_2$; 200 ppm NaCN; 21°C; 98% -400 mesh.

Effect of Pretreatment

The effect of pretreatment with or without addition of lead nitrate is shown in Figure 3.

The results indicate that a 6-hour pretreatment without lead nitrate had no effect on gold leaching kinetics and overall gold extraction, the overall gold extraction for 20-hour cyanidation was the same as the baseline test (tailings at 0.16 g/t Au). Pretreatment with lead nitrate and direct addition of lead nitrate during a straight cyanidation achieved the same gold extraction. The overall gold extraction increased by 7.0% and the gold content in the tail was reduced from 0.16 g/t Au to 0.11 g/t Au. A pre-treatment did not have an effect on the cyanide consumption. Also, the system is far away from an equilibrium state.

Effect of Lead Nitrate Addition

The effect of lead nitrate on straight cyanidation was tested at levels of 50 g/t, 100 g/t, 125 g/t and 200 g/t. The results are shown in Figure 4.

The addition of lead nitrate showed a remarkable benefit on gold leaching kinetics and over all gold extraction. Gold extractions were increased by 4.2% and 7.0% when 50 g/t and 100 g/t $Pb(NO_3)_2$ were used. The gold content in the tail was reduced from 0.16 g/t Au to 0.13 g/t and

0.11 g/t Au. No further benefit was observed if the amount of lead nitrate was increased to 125 g/t and 200 g/t. The addition of lead nitrate did not have remarkable effect on the cyanide consumption, the cyanide consumption being already very low.

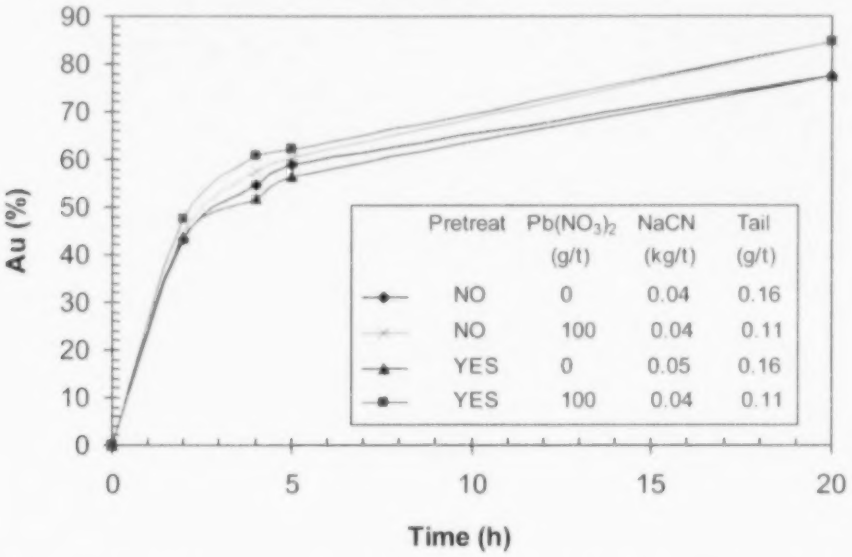

Figure 3: Effect of pretreatment with and without lead nitrate on the cyanidation of the blend sample from Fort Knox. Pretreatment: pH: 10.2; DO: 12 ppm; 10°C; 6 hours. Cyanidation: pH: 10.2; 75 ppm NaCN; 20 hours.

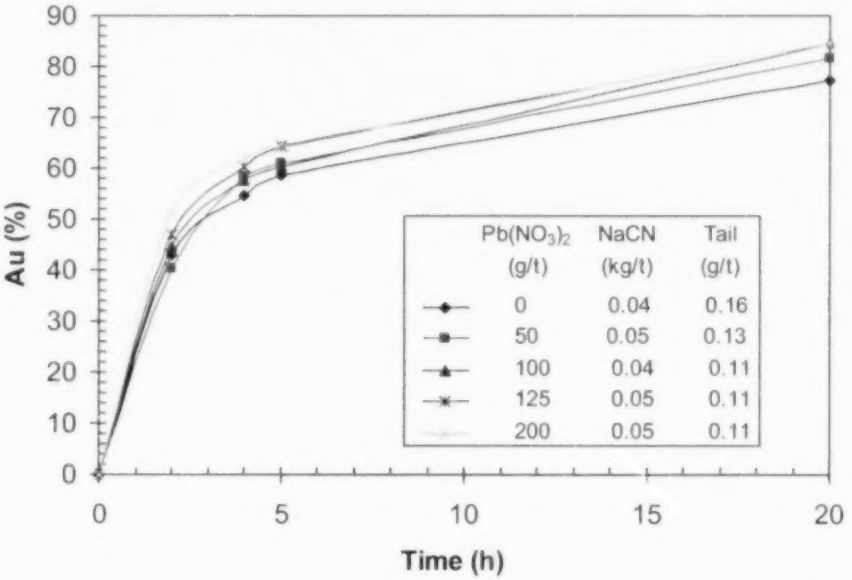

Figure 4: Effect of lead nitrate addition on a straight cyanidation of the blend sample from Fort Knox. pH: 10.2; DO: 12 ppm; 75 ppm NaCN; 10°C; 20 hours.

The improvement of the gold leaching rate was not effective enough to bring the system to a steady state within 20 hours. Improvement of the leaching rate will be addressed later with other parameters in this investigation.

Effect of Slurry pH

Trace amount of antimony minerals (stibnite, cervantite) was detected in the second True North ore sample. Since antimony could form an insoluble compound (aurostibite) on the gold surface at high pH and retard gold leaching process, the effect of pH on gold extraction of the blend sample was tested.

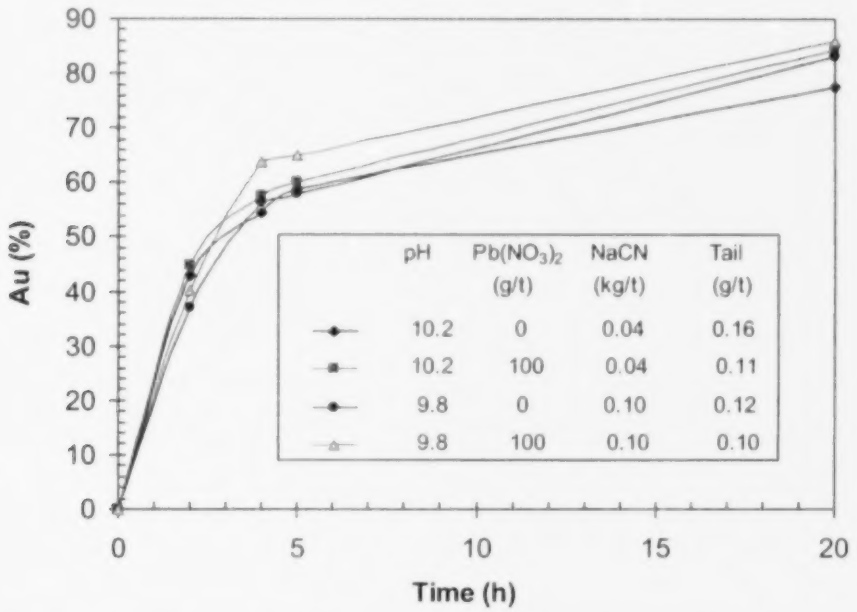

Figure 5: Effect of slurry pH on cyanidation of the blend sample from Fort Knox. DO: 12 ppm; 75 ppm NaCN; 10°C; 20 hours.

The results of Figure 5 indicate that a higher extraction was actually achieved at a lower pH. Without lead nitrate addition, the gold extraction increased from 77.5% to 83.1% when the pH was reduced from 10.2 to 9.8. The gold content in the tails was reduced by 0.04 g/t Au. The tests were performed in duplicate to confirm this trend. With 100 g/t lead nitrate addition, the gold extraction rate was almost the same with an increase of 1.4% when the pH was reduced from 10.2 to 9.8. The cyanide consumption was increased at low pH. The test results for the effect of pH indicate that antimony may have some negative effect on leaching of the gold in the blend sample and addition of lead nitrate at pH 10.2 could alleviate its negative effect.

Effect of Dissolved Oxygen Concentration

Figure 6 illustrates the effect of using a higher dissolved oxygen level on the gold leaching kinetics. In absence of lead nitrate, the oxygen enrichment of the pulp, from 12 ppm DO to

18 ppm DO improved the leaching kinetics and the overall gold extraction was increased from 77.5% to 83.1%. The gold content of the tailings decreased from 0.16 g/t Au to 0.12 g/t Au. Addition of 125 g/t lead nitrate in the oxygen enriched slurry did not further increase the overall gold extraction. The cyanide consumption appeared to be slightly affected by the enrichment of oxygen of the pulp. The oxygen enrichment did not improve the leaching rate enough to bring the system to an equilibrium state.

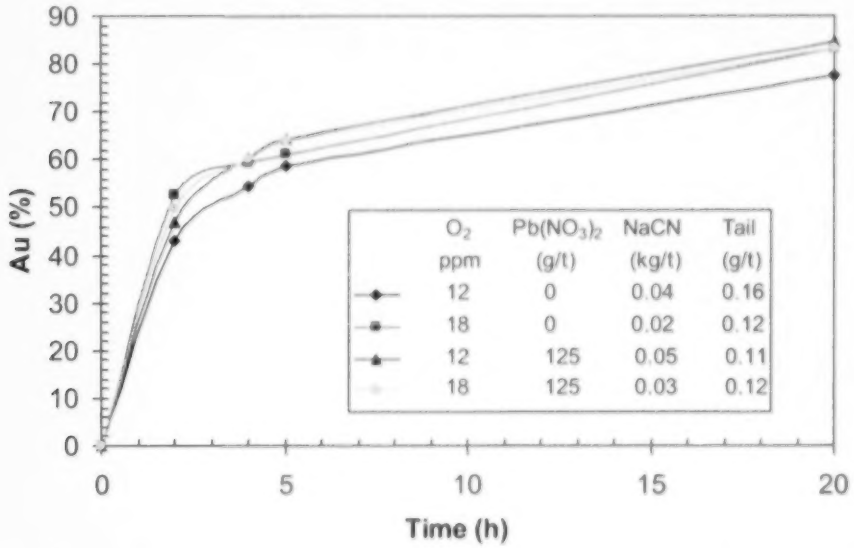

Figure 6: Effect of dissolved oxygen concentration on leaching of the blend sample from Fort Knox. pH: 10.2; 75 ppm NaCN; 10°C; 20 hours.

Effect of Cyanide Concentration

Three cyanide concentrations, 75 ppm, 100 ppm and 150 ppm, were tested to determine the effect of free cyanide concentration on the leaching kinetics and the overall gold extraction of the sample. 100 g/t lead nitrate was added in these tests. In order to obtain more details on the gold dissolution before the end, an extra liquid sample was taken at 16 hours in the first two tests. The third test, with a NaCN concentration of 150 ppm, had a duration time of 24 hours and a liquid sample was taken at 20 hours. The test results are shown in Figure 7.

The increase of sodium cyanide concentration from 75 ppm to 100 and 150 ppm resulted in higher gold leaching kinetics during the initial leaching period, and did not apparently affect the cyanide consumption. There was a faster gold dissolution with 150 ppm NaCN and the system reached a steady state in 20 hours leaching. The gold extraction remained basically unchanged with a slight increase of 1.2%. Because the cyanidation with 150 ppm NaCN appeared to reach a steady state within the retention time of the plant, it is recommended to consider using a higher free cyanide concentration in the plant.

Fort Knox Metallurgical Laboratory Results

Results of the CANMET cyanidation study on the February Fort Knox ore sample were consistent with results from the FGMI leach circuit simulation work done under similar conditions. Although the February True North composite was not tested independently at CANMET, it was used to produce the blended sample that was analyzed in the cyanidation study. This allowed for direct comparison of the CANMET findings to the FGMI laboratory results that have been correlated to actual mill performance. Table II contains the results of the CANMET and FGMI testing of both the straight Fort Knox ore sample and the Fort Knox/True North blend. Results from both labs on the blended material with lead added to cyanidation were consistent with actual mill performance in February.

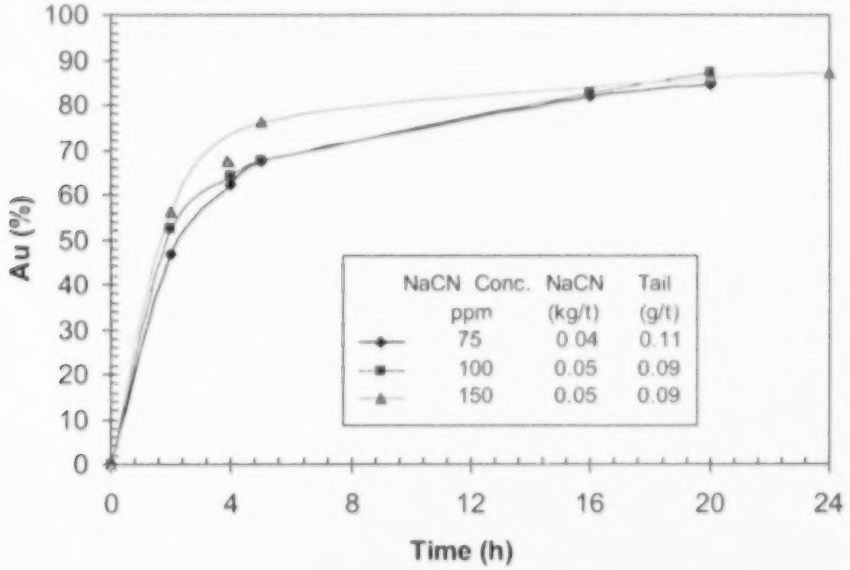

Figure 7: Effect of NaCN concentration on leaching of the blend sample from Fort Knox. pH: 10.2; DO: 12 ppm; 100 g/t $Pb(NO_3)_2$; 10°C; 20 hours.

The FGMI laboratory simulation work is performed at room temperature where the maximum dissolved oxygen that can be maintained in the bottle roll test is 6-9 ppm. And is likely the reason that it requires approximately 2 times the cyanide concentration to produce results similar to plant performance.

Table II - FGMI and CANMET Laboratory Results and February 2002 Actual Leach Circuit Performance

	FGMI Lab blend w/o lead	CANMET blend w/o lead	FGMI Lab blend with lead	CANMET blend with lead	Fort Knox actual plant With lead
Leach time, hrs	20	20	20	20	18.5
NaCN, ppm	184	76	184	76	90.5
D.O., ppm	8.4	12	8.4	12	12
Temp., °C	19.2	10	19.2	10	9.8
PH	11.35	10.2	11.35	10.2	10.1
$Pb(NO_3)_2$, g/t	0	0	75	100	70.5

Grind, % -100 mesh	64.9	65.0	64.9	65.0	84.9
Head grade, g/t	0.71	0.72	0.71	0.72	0.75
Au extraction, %	76.0	77.5	84.1	84.5	84.1

The impact of lead nitrate addition was also apparent in the leach kinetics curves. The lab procedures at the FGMI lab incorporate sampling at the 1, 2, 16, 18 and 20-hour points to allow for better definition of the extraction in the later hours. This approach allows for better prediction of the gold losses expected when increased mill throughput rates reduce circuit retention time. Figure 8 contains the kinetics data from both labs in comparison to the actual mill performance in February.

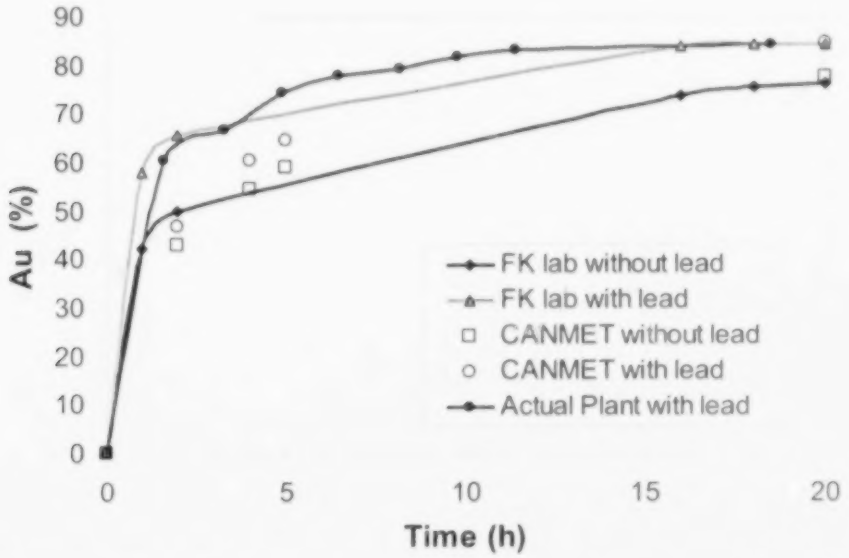

Figure 8: Effect of lead nitrate on cyanidation comparison between lab and plant results for February 2002.

With good correlation between the CANMET test results and the FGMI laboratory simulation test results on the February samples, it is concluded that any conclusions reached in the detailed CANMET study can be applied to the remainder of the 2002 FGMI test data. Process simulations tests are also performed on a blend of the True North and Fort Knox ores on a monthly basis. The gold extraction results from the monthly simulation testing of the blended samples take into account the interactions of the individual ore types and are a good indication of actual plant performance. Table III contains the expected leach extraction based on the weighted average calculation from the individual monthly ore samples and the actual results for the monthly simulations with and without lead. Also, included in Table III are the actual monthly leach circuit gold extractions.

The leaching of the blended True North/Fort Knox samples has averaged 77.0% during the first 9 months of 2002. This value is substantially less than the average calculated value of 83.9%. The laboratory leaching of the blended samples processed with lead nitrate averaged 86.1%. The gold extraction is slightly higher than the expected average value (84.5%) calculated based

on a weighted average of the results from the testing of the ores independently and was in excellent agreement with the actual average Fort Knox mill extraction of 86.2%. The results are also illustrated in Figure 9.

Table III – Actual plant and bottle roll test results on blended sample with and without lead.

Year 2002	Calculated w/o lead Leach Au Extraction %	Calculated with lead Leach Au Extraction %	FK/TN Blend w/o lead Leach Au Extraction %	FK/TN Blend with lead Leach Au Extraction %	Change Leach Au Extraction %	Actual Plant Leach Au Extraction %
Jan	83.4	85.8	75.0	84.2	9.2	86.2
Feb	84.7	87.5	76.0	84.2	8.2	84.1
Mar	85.0	84.3	78.1	87.7	9.6	84.8
Apr-	77.4	82.0	85.3	88.3	3.0	87.4
May	86.3	84.7	63.8	86.5	22.7	87.8
Jun	87.3	87.6	76.0	88.8	12.8	87.8
Jul	85.8	84.1	79.3	85.5	6.2	86.1
Aug	80.1	79.1	78.7	85.6	6.9	85.7
Sep	85.1	85.2	80.7	84.5	3.8	85.8
Average	83.9	84.5	77.0	86.1	9.1	86.2

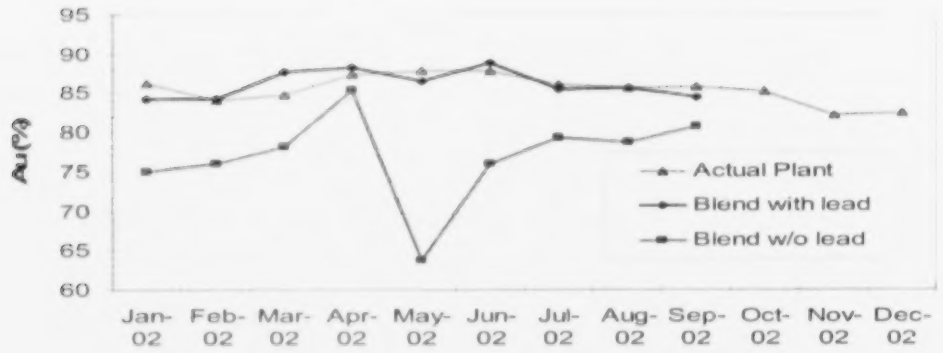

Figure 9: Comparison of plant performance with laboratory simulation test with and without lead.

The simulations were initially performed on a standard 3:1 ratio of Fort Knox to True North in 20 hour cyanidation tests. The procedure was modified during the year and improved the correlation in the results from the simulations with lead and the actual leach plant performance. The primary changes included adjusting the duration of the simulation test time to represent the average circuit retention time each month and developing the blended sample based on the actual average blend ratio processed for the month.

The high variability in the test results between the simulations with lead and without, specifically for the May composite, is apparent in both Table 3 and in Figure 8. Multi-element ICP analysis was performed on all simulation test feed and tail solid samples and solution samples. Results of multi-element analysis indicated that leach gold extractions strongly correlated with the antimony content of the feed sample with leach extraction decreasing as the antimony content of the feed material increased. This relationship was virtually eliminated when lead nitrate was added to cyanidation tests. Consequently, the negative effect of antimony can be compensated for through a lead nitrate addition. These relationships are contained in Figure 10.

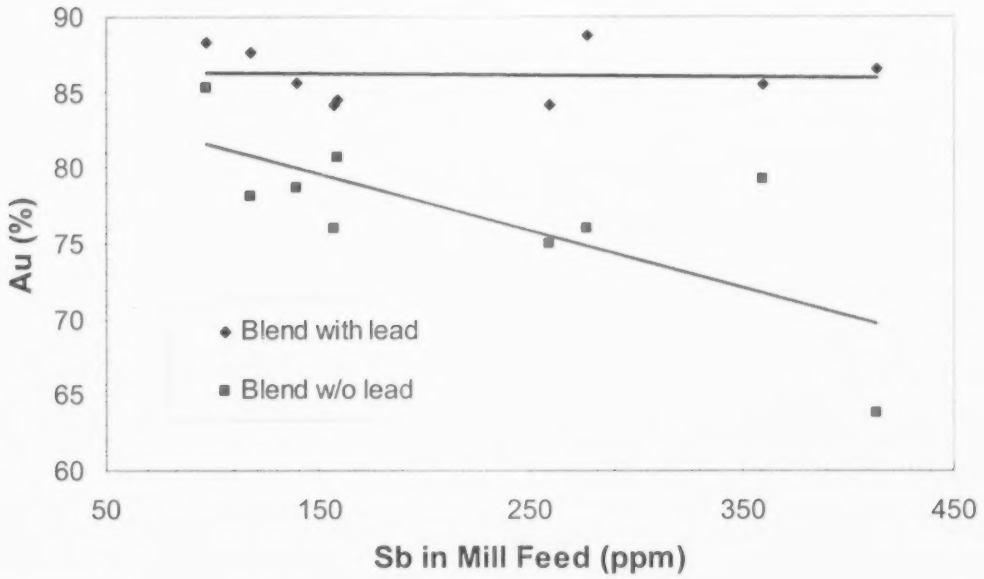

Figure 10: Effect of antimony concentration in the feed on the cyanidation of blended mill feed composites with and without lead nitrate.

Lead nitrate has been added to the Fort Knox leach circuit on a continuous basis since late December 2001. Therefore, no direct comparison between processing with lead and without lead can be provided for the plant. However due to the strong correlation between the results of the lab simulation tests with lead addition and the actual plant performance, it is assumed that the results of the FGMI laboratory data simulate adequately the difference of using lead addition to predict plant performance. It is estimated that gold production from the Fort Knox mill was increased by 31,200 ounces in 2002 due to the addition of lead nitrate. With total lead nitrate spending of $980,000 in 2002, the cost per incremental ounce produced was approximately $31.

The FGMI laboratory simulation procedure was developed for metal accounting and recovery calculations and was not intended for predicting reagent consumptions. Although the average consumptions were consistent (0.065 kg/t plant, 0.067 kg/t lab), the correlation between the

monthly data is poor. Additional work is required to explain the variation in the monthly cyanide consumption data measured in the FGMI laboratory.

Discussion

The laboratory results from FGMI correlated strongly with the CANMET laboratory results. The laboratory results of cyanidation without lead under typical circuit conditions (65% -100 mesh grind, D.O. of 12 ppm, free cyanide concentration of 75 ppm NaCN and pH 10.2) were found to be approximately 77%. The extraction could be increased to approximately 84% by reducing pH to 9.8, increasing D.O. concentrations to 18 ppm or through the addition of 100 ppm lead nitrate. The 84% laboratory extraction was consistent with plant extraction and the best leaching parameters were found to be identical to the base line parameters currently used in the plant. The system however did not reach a steady state in 20 hours and pretreatment did not show any significant advantage over straight cyanidation.

The concentration of antimony is similar to the feed processed at Williams Mine of Hemlo [6] where cyanidation at a pH below 10 is used to minimize the negative effect of antimony on gold extraction. Although reduction of the pulp pH proved to be efficient in laboratory tests, it is not an option in the Fort Knox mill where operating the circuit at a reduced pH results in above threshold level HCN concentrations in the tank enclosures. The enclosures are required to allow the circuit to be operated and maintained in a sub-Arctic environment.

At a free cyanide concentration of 150 ppm, the gold leaching kinetics were significantly improved and the system reached a steady state, however, the overall extraction was not significantly improved. The higher cyanide concentrations were not detrimental on cyanide consumption in the CANMET laboratory test. However in plant practice, only 60% of the barren leach solution is recycled and the remainder requires cyanide destruction. Consequently, using higher cyanide concentrations in leach circuit not only increases reagent costs for cyanide but also increases the detox circuit reagent costs and close consideration of the incremental cost per ounce produced is required when setting the optimum NaCN concentration for the plant.

Conclusions

The mineralogical study indicated that the blend sample contained 99% gangue minerals, little amounts of pyrite, arsenopyrite and pyrrhotite and trace amounts of stibnite, cervantite, arseniosiderite, scorodite and chalcopyrite. The leachable gold of the feed was found at the CANMET laboratory to be 95.8%. The presence of antimony interferes with gold leaching. The addition of lead nitrate is the most practical and cost effective way to alleviate the negative effects of antimony on gold leaching. In the year 2002, the new scheme increased the gold extraction by 7-9% and resulted in gold production being in excess of 31,000 ounces higher than that estimated for the non-lead nitrate reagent scheme. The uses of a pH below 10 as well as a higher dissolved oxygen of the pulp are also options to improve the gold extraction in presence of antimony. The use of low pH is not a practical alternative because of the generation of HCN concentrations in the tank enclosures required to be operated and maintained in a sub-Arctic environment.

The laboratory results at CANMET correlate strongly with the results at FGMI and the results from both labs correlate well with the performance of the plant which indicates that the approach used in the labs is reliable.

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